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Tropical Cyclone Hazards in the USA

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Abstract
Coastal development, population, and hurricane activity are all projected to increase in the near future. Thus, the USA has a tropical cyclone problem that requires interdisciplinary solutions from physical and social scientists. In this article, we review topics that summarize the current state of hurricane hazards in the USA. A review of meteorological hurricane hazard literature is broken into sections discussing wind and water hazards associated with land-falling tropical cyclones. This section is followed by a review of societal impact literature such as mortality and morbidity, hazard perception, communication, evacuation, and risk. Ideas are presented which introduce suggestions on how to possibly change processes and promote cross-dialog that may alleviate both the physical and societal impacts of tropical cyclones in the USA.

1. *Introduction*

The USA has a hurricane problem. Annually, tropical cyclones (TCs) making US landfall result in estimated losses of $5–10 billion (Bengtsson 2001; Pielke et al. 2008). These losses are due, in part, to the rapid increase in population, per capita wealth, property values, and coastal development over the previous decades (Pielke et al. 2005; Schmidt et al. 2009). During the past decade, it was estimated that 53% of the US population resided in coastal counties (Crossett et al. 2004), with approximately 19 million people living within 1 km of the shoreline in the conterminous USA. Almost 12 million of these coastal residents live below 3 m elevation, especially in Florida (Lam et al. 2009). Coastal population growth and development may continue to escalate in the coming decades (Crossett et al. 2004) in a time period when TC activity has the potential to be higher than historical levels (Emanuel 2005). It should be noted, however, that there are no discernible trends in historical damage estimates when adjusting for inflation, although the decade 1996–2005 was the second most costly decade in US history (Pielke et al. 2008). The repeated intersection of these two trajectories over time, coastal development and increased hurricane activity, may result in a greater emphasis upon interdisciplinary social and physical science solutions involving TC hazard mitigation, education, assessment, and resiliency. Due to interdisciplinary training, geographers are ideally suited to find solutions to these problems.

In this article, we discuss both physical and social aspects of TC impacts in the USA. We begin by summarizing TC characteristics and physical hazards. This is followed by a section on meteorological hazards, divided into water and wind hazards and discussed separately. The discussion then shifts to societal impacts with sections on mortality and morbidity, evacuation, hazard perception, and risk. In the final concluding section, we identify topical areas and offer suggestions on areas to better integrate these topics to study the hurricane problem in the USA.

2. *Characteristics Associated with TCs*

The document-based historical record of TC occurrences extends back over 1000 years in southern China (Liu et al. 2001) and to the late 17th century in the Atlantic and Caribbean basins (Chenoweth 2006). Use of newspaper reports, ship logs, diaries, letters, and government documents have allowed for individual TCs to be tracked and intensities estimated (Chenoweth 2003, 2006; Chenoweth and Divine 2008; Ludlum 1963; Mock 2004, 2008; Mock et al. 2010; Scheitlin et al. 2010). These results have been compared to proxy data used in paleotempestology analyses to assess the variability and patterns in TC impact, strength, and occurrence (Liu 2004; Liu et al. 2001, 2008; Nott 2004). Following the many technological advances in weather observing systems, more detailed, storm-specific analyses and climatologies have addressed temporal and spatial variability in TC formation, movement, intensity, and environmental conditions (Elsner 2003; Elsner and Liu 2003; Elsner et al. 1999, 2000; Harr and Elsberry 1991; Ho et al. 1987; Lander 1996; Landsea 1993; Nuemann et al. 1999; Xie et al. 2005). Climate modeling studies have attempted to characterize future TC activity based on a variety of future atmospheric and energy budget scenarios (Bengtsson et al. 1995; Elsner 2006; Emanuel 2005; Holland and Webster 2007; Knutson and Tuleya 2004; Knutson et al. 1998, 2010; Landsea 2005; Pielke et al. 2005).

Tropical cyclone intensity has routinely been assessed using minimum central pressure, wind, rain, and storm surge. The pressure–wind relationships developed for the Atlantic and Pacific basins have been used to assess storm morphology and strength (e.g. Atkinson and Holliday 1977; Dvorak 1975; Holland et al. 2010; Knaff and Zehr 2007; Willoughby 1990). Wind within the TC also varies considerably depending on location to the central eye feature (Bell and Ray 2004; George and Gray 1976; Merrill 1984; Vickery and Twisdale 1995) and in relation to the size of the eye and eye wall replacement cycles, which have been shown to rapidly intensify TCs in short time periods (Bell and Montgomery 2008; Croxford and Barnes 2002; Kaplan and DeMaria 2003; Möller and Montgomery 2000; Willoughby et al. 1982).

Precipitation in TCs has generally been assessed in three environments: over open water, as TCs approach and make landfall, and as TCs move inland and decay or transition into extratropical systems. The convective, heavy precipitation is typically found in the inner core of the TC, near the eye feature (Cecil et al. 2002; Cerveny and Newmann 2000; Marks 1985; Marks and Houze 1987) and in the outer rain bands (Hood et al. 2006; Jorgensen et al. 1985; Marks 1985; Zipser and LeMone 1980). Stratiform precipitation is also present in TCs and is possible in all regions of the storm, primarily due to uplift and latent heat dynamics (Houze 1982, 2004; LeMone and Zipser 1980; Yokoyama and Takayabu 2008; Zipser 1977). Analyses of pre- and post-landfall precipitation in TCs have revealed distinct shape characteristics and precipitation intensity variation as a result of the changing atmospheric environment from ocean to land (Atallah and Bosart 2003; Atallah et al. 2007; Dong et al. 2010; Elsberry 2002; Marks and Houze 1987; Matyas 2007, 2010). Assessing the precipitation potential in TCs at landfall and after is extremely important because rain rates do not correlate well with storm intensity (Griffith et al. 1978; Jiang et al. 2008). The combination of minimum central pressure, wind, and shoreline characteristics provide the impact potential for storm surge. Open water TC characteristics have been used to estimate and predict storm surge potential along the coastline with varying degrees of success (e.g. Berke et al. 1984; Harris 1959; Hoover 1957; Jelesnianski 1972). The relationship between storm surge and storm intensity is not simple, with multiple studies revealing the importance of understanding the landfall location, movement, forward speed, and the near-coastal topography (Weisberg and Zheng 2006) and storm energy as a predictor of surge potential (Powell and Reinhold 2007). More-recent work by Irish et al. (2008) has shown storm size to be a reasonable predictor of surge potential with land-falling TCs.

Tropical cyclone activity in the Atlantic basin varies considerably on annual and decadal time scales. Global and synoptic scale pressure and sea surface temperature (SST) oscillations explain much of the variance in activity. For example, the Atlantic Multidecadal Oscillation (AMO) is a naturally occurring 20- to 40-year SST oscillation measured in the Atlantic Ocean (Schlesinger and Ramankutty 1994). It consists of a positive and a negative phase in which the positive phase is characterized by warmer SST and increased hurricane activity in the Atlantic Basin. The relationship between Atlantic hurricane activity and the AMO is often expressed by viewing the relationship between annual storm count and AMO phase. Accumulated Cyclone Energy (ACE) (Bell et al. 2000; Yu et al. 2009), combining wind speed and duration of the storm, is another popular method used to assess the significance of an individual event or cumulative TC significance over a season. ACE in the Atlantic Basin displays a better relationship with annual AMO ($r^2 = 0.28$) (Figure 1) than annual TC count and annual AMO (Spearman's $r^2 = 0.18$).

Since 1995, the USA has experienced many active hurricane seasons in the positive phase of the AMO which is likely to persist through at least the next decade (Goldenberg et al. 2001). As stated earlier, normalized damage from this positive AMO period from 1996–2005 is second only to the decade 1926–1935, which was also the first decade of the onset of a positive AMO period (Pielke et al. 2008). Caution must be employed in reaching conclusions regarding normalized damage trends over time and AMO phase. Of the top 15 most damaging hurricanes, many occurred during negative AMO phases including Camille (1969) and Andrew (1992). Furthermore, 70% of the damage from 1926 to 1935 is represented by the 1926 Great Miami/AL hurricane, and 40% of the damage from 1996 to 2005 is represented by Katrina (2005) (Pielke et al. 2008).

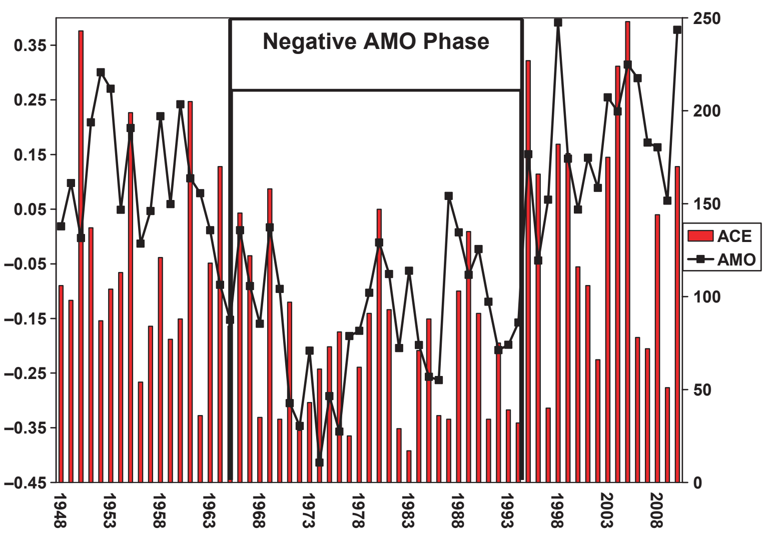

Fig. 1. Annual Unsmoothed AMO and ACE values for the North Atlantic 1948–2010. AMO values are SST anomaly while ACE is measured in 10^4 kts^2. Adapted from: http://www.aoml.noaa.gov/hrd/tcfaq/E11.html (ACE values) http://www.esrl.noaa.gov/psd/data/climateindices/list/ (Unsmoothed AMO) http://www.coaps.fsu.edu/~maue/tropical/index.html (2010 ACE value).

Although the AMO is currently positive, not every year in this phase is characterized by excess activity. Annual variation in Atlantic activity is influenced by ENSO phase. During El Niño (La Niña) years, Atlantic hurricane activity decreases (increases) and US landfalls also decrease (Smith et al. 2007) due to an active (inactive)subtropical jet and more (less) turbulent wind shear across the hurricane formation region in the Atlantic (http://iri.columbia.edu/climate/ENSO/globalimpact/TC/Atlantic/windshear.html). Thus, it is possible to have an inactive (active) Atlantic hurricane season, like 2009 (2010) that is both positive AMO and El Niño (positive AMO and La Niña). In El Niño (La Niña) season 2009 (2010), there were nine (19) named TCs in the Atlantic Basin. Furthermore, the longevity and intensity of TCs is possibly being influenced by global climate change (Emanuel 2005; Holland and Webster 2007; Knutson and Tuleya 2004; Landsea 2005; Pielke et al. 2005; Shepherd and Knutson 2007; Webster et al. 2005). This is a rather contentious debate that is difficult to resolve and is not the primary focus of this article. Nevertheless, it is safe to conclude that the USA will likely see increased TC activity in the coming decade with the possibility of climate change modifying projections of future activity.

3. *Physical Hazards*

The Saffir–Simpson (SS) (Simpson 1974) scale is the official metric by which TC intensity is measured in the Atlantic Basin. It is a simple 1–5 categorical warning scale for the pre-landfall period, now assessing wind speed only. Similar operational warning scales exist around the world (Senkbeil and Sheridan 2006). Over the years, researchers have proposed alternative hurricane scales (Kantha 2006; Powell and Reinhold 2007; Sallenger 2000; Senkbeil and Sheridan 2006), accenting SS scale limitations. Commonly TC warning scales emphasize wind over open water environments as the primary variable to classify hurricane intensity. While wind is an important TC hazard, it diminishes rapidly after landfall, thus reducing its importance as the primary TC hazard for the majority of storms (Kaplan and DeMaria 1995, 2001). Furthermore, for strong TCs most low-elevation coastal areas are evacuated so that displaced residents experience TC impacts from a more inland perspective as wind is decreasing. In order for residents to have a more accurate understanding of hazards that may affect them, emphasis should be placed on a wider range of hazards across the coastal to inland transition.

Tropical cyclones produce a variety of meteorological hazards during and after landfall. Some of the direct and indirect meteorological hazards include: storm surge, heavy precipitation/flooding, sustained winds, wind gusts, falling trees, and tornadoes. The most fatal hazard varies by location as a function of two variables; distance from the coast and elevation above sea level. Water hazards, such as storm surge and inland flooding, are more lethal than wind hazards, such as high winds and tornadoes. Storm surge is the primary concern in low elevations immediately adjacent to the coast (Colle et al. 2008; Davis et al. 2004). Farther inland at higher elevations, the primary hazard is heavy precipitation. Inland flooding produces more fatalities in land-falling TCs than any other hazard (Rappaport 2000). The threat from wind hazards depends on the intensity of the storm at landfall, its forward speed, and an individual storm's propensity to produce tornadoes. Given the variability in TC hazards based on location, the objective of the physical section of this article is to provide readers with a review of the scientific literature assessing the direct and indirect meteorological hazards associated with land-falling TCs.

3.1 WATER HAZARDS

Storm surge is an onshore surge of seawater that is primarily a result of TC winds and, to a lesser extent, the surface pressure gradient near the center of the storm. The magnitude of the TC-induced storm surge is a result of the size, intensity, and forward movement of the storm. The shape of the coastline and the sub-surface topography of the near-shore environment also play an integral role in determining surge magnitude. Early storm surge analyses employed statistical models to predict TC surge events based on storm characteristics and regional bottom slope (e.g. Conner et al. 1957; Harris and Angelo 1963; Hoover 1957). Numerical modeling provided additional insight with advances in computing power (e.g. Crawford 1979; Jelesnianski 1972; Jelesnianski et al. 1992; Westerink et al. 2008) when comparing to storm surge case studies (Jelesnianski et al. 1992). The most widely applied model, the Sea, Lake, and Overland Surges for Hurricanes (SLOSH) model developed by the National Weather Service (Jelesnianski et al. 1992) provided a real-time forecasting tool to provide TC-specific predictions of surge potential based on surface topography, coastal bathymetry, and water bodies adjacent to the shoreline. The relative simplicity of the model allowed for accurate storm surge prediction without detailed storm characteristics, allowing for rapid dissemination of surge prediction in the days and hours prior to landfall. The SLOSH model has been used in additional storm surge modeling and case studies to fine tune basin and storm-specific parameters for increased accuracy (Houston et al. 1999; Irish et al. 2008; Lin et al. 2010).

Early studies by Conner et al. (1957) and Hoover (1957) considered central storm pressure as the most important factor in determining storm surge along the Gulf of Mexico and Atlantic coasts. These studies noted that factors such as forward speed, the radius of maximum winds, and the angle of landfall are important to consider, but not as vital as central pressure. The development of additional numerical storm surge models highlighted the importance of considering additional meteorological elements (Berke et al. 1984; Blain et al. 1998; Jelesnianski 1972, 1984; Westerink et al. 2008). However, given the importance placed on the Saffir–Simpson scale, storm surge analyses commonly focused on storm intensity as a predictor for storm surge (Irish et al. 2008). More recently, analyses have included storm size as a predictor for storm surge. Irish et al. (2008) found storm size does indeed play an integral role in storm surge generation, especially for intense TCs and in regions with very shallow near-shore slopes (Table 1). Additionally, faster-moving storms have a tendency to produce storm surges of greater height but of shorter duration (Resio et al. 2009). Ultimately, storm surge is a response to multiple meteorological and bathymetric factors that will change based on the individual character of a TC and its land-falling location.

Heavy rainfall and flooding associated with TCs develop as a result of complex interactions between the inland terrain, the TC, and under varying atmospheric conditions. Understanding and assessing precipitation impacts is extremely important since the combination of physical and social elements can lead to extraordinary flood occurrences when storm dynamics interact with local influences (e.g. Shepherd et al. 2010). Precipitation from TCs is an important contributor to annual precipitation in many locations in the USA (Cerveny and Newmann 2000; Knight and Davis 2007; Lau and Wu 2007). Precipitation associated with TCs and extreme rainfall events are more common during the peak of TC season, during September and October (Shepherd et al. 2007). Knight and Davis (2007) found TC-related precipitation has increased over the southern and eastern coastal regions of the USA since 1980. Increases were also noted in extreme TC precipitation events (Easterling et al. 2000).

Table 1. Characteristics of surge associated with land-falling central pressure, SS category, radius to maximum wind, and continental shelf slope. Note the differences between Katrina and Camille which both made landfall at the same location. From Irish et al. (2008).

Storm date (name)	Central pressure (mb)[a]	Radius to maximum wind (km)[b]	Saffir–Simpson category[c]	Estimated influencing continental shelf slope	Observed open coast surge (m)
October 1941 (unnamed)	970	33	2	1:2000–1:3500	3.2[d]
October 1944 (unnamed)	960	58	3	1:1500–1:1700	2.3–3.4[d]
June 1957 (Audrey)	964	46	4	1:4000	3.4–3. 8[d]
September 1961 (Carla)	936	56	4	1:1000–1:1700	3.3–3.7[e]
September 1964 (Hilda)	960	39	3	1:4000–1:7500	2.3–3.0[f]
August 1965 (Betsy)	945	74	3	1:5000–1:10,000	4.1–4.8[f]
September 1967 (Beulah)	950	46	3	1800–1:1100	2.4–2.9[g]
August 1969 (Camille)	910	22	5	1:5000–1:10,000	6.4–6.9[f]
July 1970 (Celia)	944	17	3	1800–1:1100	2.7–2.8[h]
August 1974 (Carmen)	943	28	3	1:2500	
August 1979 (Frederic)	950	46	3	1:1500–1:1900	3.5–3.8[i]
July 1980 (Allen)	945	37	3	1800–1:1100	2.1–3.7[h]
August 1992 (Andrew)	949	30	5	1:750–1:1500	2.4[j]
October 1995 (Opal)	940	69	3	1:750–l:l000	3.1–3.7[k]
August 1999 (Bret)	953	19	3	1:800–1:1100	0.9–1.5[l]
September 2002 (Lili)	966	28	1	1:4000–1:7500	3.2–3.6[f]
September 2004 (Charley)	950	19	4	1:500–1:1000	2.1
September 2004 (Ivan)	955	56	3	1:1500–1:1900	3.0–3.1[m]
July 2005 (Dennis)	952	11	3	1:750–1:1500	1.7–2.5[n]
August 2005 (Katrina)	919	47	3	1: 5000–1:10,000	7.5–8.5[b]
September 2005 (Rita)	946	40	3	1:2500–1:3000	3.0–4.6[o]
October 2005 (Wilma)	951	73	3	1:500–1:1000	1.8–2.4[p]

[a]National Weather Service (2000)
[b]U.S. Army Corps of Engineers (2006a)
[c]Blake et al. (2006)
[d]Harris (1963)
[e]Ho and Miller (1982)
[f]U.S. Army Corps of Engineers (2006b)
[g]U.S. Army Corps of Engineers (1968)
[h]National Weather Service (2000)
[i]U.S. Army Corps of Engineers (1981)
[j]National Weather Service (1993)
[k]U.S. Army Corps of Engineers (1995)
[l]Lawrence and Kinberlain (2001)
[m]National Weather Service (2005)
[n]National Oceanic and Atmospheric Administration (2005)
[o]Knabb et al. (2006)
[p]Pash et al. (2006)

The potential for heavy rain and flooding is often a result of the TC interacting with the synoptic and mesoscale atmospheric environments at landfall and in the days following, at which point extratropical transition occurs. TCs undergoing extratropical transition produce more precipitation to the left of the storm track when interacting with a down-stream trough, while more precipitation on the right side of the storm track is common when the TC interacts with a ridge (Atallah et al. 2007). Cerveny and Newmann (2000) found more intense TCs produce more precipitation in the outer rain bands and in the inner core of land-falling storms. The impact of extratropical transition is significant since a majority of inland heavy rain and flooding events are a result of this process (Bosart and Dean 1991; Palmén 1958). This potential is amplified as the TC season progresses due to the more meridional flow during the later portion of the storm season (Foley and Hanstrum 1994). Precursor rain events (Galarneau et al. 2010) have been defined as heavy precipitation events occurring well in advance (as far as 1000 km from the storm) of a land-falling TC. Precursor heavy rain events are more common in August and September and usually occur approximately 36 h prior to landfall, as was the case with TC Erin in 2007 (Galarneau et al. 2010).

3.2 WIND HAZARDS

Nontornadic winds in the outer rain bands and inner core are a major component of TCs (Emanuel et al. 2006; Lee and Bell 2007; McDonald 1935; Powell 1982; Willoughby and Black 1996). Research on TC wind hazards has focused on the dynamics of open water conditions (Holland 1980; Powell 1982; Powell et al. 1991; Vickery and Skerlj 2000; Vickery and Twisdale 1995) and at TC landfall (Powell and Houston 1998; Tuleya and Kurihara 1978; Tuleya et al. 1984; Vickery et al. 2009; Wakimoto and Black 1994; Zhu 2008) through modeling and case studies. TC-force winds diminish rapidly after landfall due to surface friction and a loss in available energy and latitudinal location of landfall (Figure 2) (Kaplan and DeMaria 1995, 2001). There are several factors that influence TC wind intensity at landfall. As noted by Sparks (2003), the Saffir–Simpson TC intensity scale provides guidance on storm strength based on open water calculations, which can become more error-prone when landfall occurs. Previous research has addressed the transition and decay of TC winds at landfall as a result of the forward speed

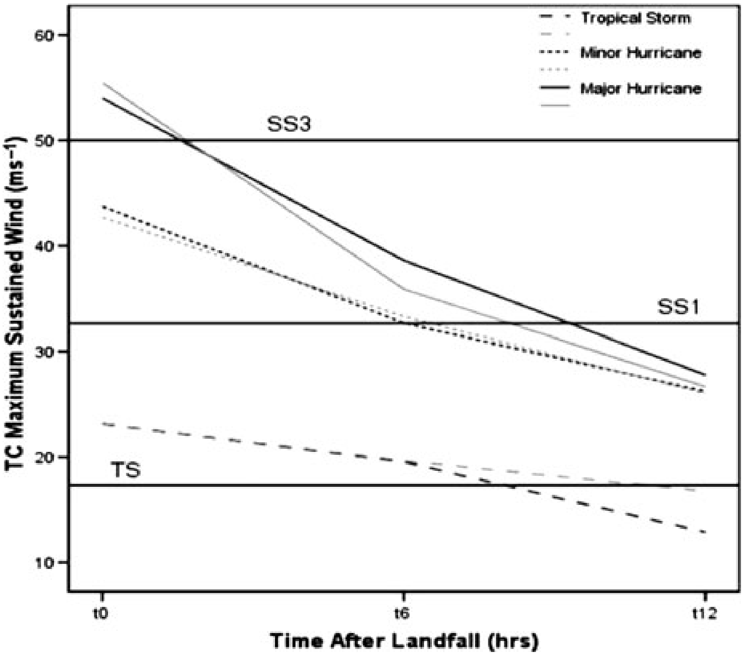

Fig. 2. Mean (dark) and median intensity decay rates for land-falling US TCs since 1995.

and intensity (Kaplan and DeMaria 1995, 2001; Tuleya et al. 1984), noting that forward speed is as important as storm intensity (Kaplan and DeMaria 2001) as well as landfall location along the US coast (Jagger and Elsner 2006). Even with winds weakening following landfall, wind-related hazards from falling trees accounted for 31% of all TC deaths (Schmidlin 2009). This can be exacerbated when heavy rains weaken soil structure, promoting premature tree failure.

A large body of literature has also addressed the occurrence of TC-induced tornadoes (e.g. Baker et al. 2009; Belanger et al. 2009; Gentry 1983; Hill et al. 1966; McCaul 1991; Novlan and Gray 1974; Smith 1965; Verbout et al. 2007). The threat from TC-spawned tornadoes is usually greatest within 3–4 days of landfall (McCaul 1991; Schultz and Cecil 2009), with over 90% occurring within 400 km of the coastline (Schultz and Cecil 2009). TCs making landfall in the southern USA have a greater potential for tornado formation than TCs making landfall along the eastern USA due to the more favorable shear environment due to southern TCs recurving to the north and northeast, as opposed to the westerly moving east coast storms (Gentry 1983; McCaul 1991; Novlan and Gray 1974; Verbout et al. 2007). TC size and intensity have also been shown to have an impact on tornado occurrences along coastal areas (Hill et al. 1966; McCaul 1991; Schultz and Cecil 2009; Verbout et al. 2007). Tornadoes are most common in the outer rain bands of TCs, but have also developed near the inner core of the storm (Baker et al. 2009; Hill et al. 1966).

Structurally, TC tornadoes have shallower circulations than tornadic supercell thunderstorms over the central USA (McCaul 1987, 1991; McCaul and Weisman 1996). TC tornadoes have higher moisture content, lower values of CAPE, and very high values of boundary layer wind shear (Bogner et al. 2000; Novlan and Gray 1974) and typically do not present the same characteristic radar signatures (Spratt et al. 1997). Nevertheless, the impact of TC tornadoes can be significant, with approximately $1.4 billion in damages during the 1950–2007 time period (Schultz and Cecil 2009). Tornado formation is not uniform within a TC, however, as most tornadoes occur in the right front quadrant/region of storm (Gentry 1983; Hill et al. 1966; McCaul 1991; Novlan and Gray 1974), whether the location is defined relative to true north (Orton 1970) or relative to TC motion (Schultz and Cecil 2009).

4. *Societal Impacts and Hazards*

4.1 MORTALITY AND MORBIDITY

Fatalities from TCs in the USA have been steadily decreasing presumably as warning technology has increased over time (Lazo et al. 2010). One notable exception to this trend is Hurricane Katrina. The unique attributes of the storm's intensity, high surge, and heavy precipitation combined with unfortunate social and political circumstances to result in at least 1500 fatalities. According to a technical memorandum issued every few years by NOAA/NWS/TPC (Blake et al. 2007) Katrina ranks third in TC fatalities from landfalling US storms since 1900, and it is the only storm in the top 10 since Hurricane Audrey in 1957 (Table 2).

While the numbers of fatalities have been reduced over time, Czajkowski and Kennedy (2010) suggest that the result may be overstated considering higher evacuation rates from recent storms among other factors. Using empirical modeling, a higher than expected count of fatalities was found for counties frequently struck, especially those near the Gulf of Mexico. A lower than expected count of fatalities was observed for counties with

Table 2. US tropical cyclones with highest fatalities since 1851. From Blake et al. (2007).

Rank	Hurricane	Year	Category	Deaths
1	TX (Galveston)	1900	4	8000[a]
2	FL (SE/Lake Okeechobee)	1928	4	2500[b]
3	*Katrina* (SE LA/MS)	2005	3	1500
4	LA (Cheniere Caminanda)	1893	4	1100–1400[c]
5	SC/GA (Sea Islands)	1893	3	1000–2000[d]
6	GA/SC	1881	2	700
7	*Audrey* (SW LA/N TX)	1957	4	416[h]
8	FL (Keys)	1935	5	408
9	LA (Last Island)	1856	4	400[e]
10	FL (Miami)/MS/AL/Pensacola	1926	4	372

[a]Could be as high as 12,000
[b]Could be as high as 3000
[c]Total including offshore losses near 2000
[d]August
[e]Total including offshore losses is 600
[f]No more than
[g]Total including offshore losses is 390
[h]At least

higher numbers of residents 65 years of age or older, under 18, and those living in poverty. Additionally, they conclude that improvements in forecasting technology have played only a minor role on the expected counts of fatalities.

Many fatalities from hurricanes occur during the post-landfall period persisting for weeks and sometimes months, typically considered to be indirect deaths. During the active 2004 and 2005 hurricane seasons in Florida, eight hurricanes made landfall resulting in 213 deaths, with most aged 40 and older. An average of 60% of the deaths occurred in the post-landfall period and approximately 80% of the deaths were attributed to accidents with trauma being the leading cause of death; followed by drowning, carbon monoxide poisoning, and electrocution (Ragan et al. 2008). In a somewhat contrasting study during the 2004 hurricane season in Florida, McKinney et al. (2010) found elevated direct and indirect mortality for up to 2 months following each of the four hurricane landfalls in Florida. Direct trauma related deaths accounted for only 4% of storm-related mortality while elevated indirect mortality was linked to heart-related (34%), cancer-related (19%), accident-related (9%), and diabetes-related deaths (5%). The elevated mortality in McKinney et al. (2010) is significantly greater than Ragan et al. (2008), which raises questions regarding the methods used in accurately assessing indirect mortality.

Morbidity is a nebulous term that may refer to physical injuries, mental illness, or disease following a TC. Morbidity has been studied in the wake of several major hurricane events (Bayleyegn et al. 2006; Brewer et al. 1994; David et al. 1996; Kessler et al. 2006; Lee et al. 1993; Longmire and Ten Eyck 1984). Prevalence of psychiatric morbidity commonly follows the strongest hurricanes. After Andrew in Florida 1992, 51% of previously non-ill subjects from high impact areas met criteria for new onset disorders, such as post-traumatic stress, depression, and anxiety disorders (David et al. 1996). Following Hurricane Katrina, survey research indicated a significant increase in severe mental illness and a more significant increase in moderate mental illness; however, suicidality significantly decreased (Kessler et al. 2006). Morbidity associated with injuries and disease varies by location. After Hurricane Andrew, a variety of conditions were commonly cited at civilian and military care sites. Injuries were the most common, followed by dermatologic illness, respiratory illness, and gastrointestinal illness (Lee et al. 1993). Inland morbidity from Hurricane Hugo showed a slightly different pattern. Almost 2100 patients at seven hospital emergency departments were treated for injuries or illness. Of these, the vast majority were treated for either wounds or insect stings with one-third of the wounds being associated with chain saws (Brewer et al. 1994). Readers should also be referred to the Centers for Disease Control who publishes Morbidity Mortality Weekly Report after hurricane landfalls.

4.2 EVACUATION, HAZARD PERCEPTION, AND RISK

A large volume of literature has been published on aspects of warning communication and interpretation, risk perception, and evacuation response (Dash and Gladwin 2007). These topics are often inseparable and are treated as such in this brief review. Behavioral and social response to hurricane evacuation has been researched numerous times since the 1950s (Baker 1979, 1980, 1986, 1990, 1991, 1995; Dash and Morrow 2000; Dow and Cutter 1998, 2002; Killian 1954; Lindell et al. 2001, 2005; Moore et al. 1963; Wilkinson et al. 1970; Wilmot and Mei 2004; Windham et al. 1977). Baker (1991) indicated that aggressive warning from public officials and effective dissemination of warnings elicited the greatest evacuation response rates from high risk mandatory zones. Furthermore, a perceived risk of one's home being flooded was another strong determinant of evacuation. General hurricane knowledge, hurricane safety awareness, and prior experiences were not reliable predictors of evacuation response. Dow and Cutter (2002) discussed hurricane savvy populations that no longer needed to wait for official evacuation orders. Lindell et al. (2005) discovered that during the evacuation of Hurricane Lili in 2002, residents from high risk areas showed a more significant reliance on local news media and the internet compared to those in lower risk regions. Local television or cable television (Weather Channel) is frequently the most common form of media used for updates on storm-specific information and changes to risk areas; however, in 1998 internet web sites began to be listed as a source of information (Piotrowski and Armstrong 1998). Wilmot and Mei (2004) also cite the importance of official evacuation warnings, but discuss the growing role of local media in assisting residents in making a personal risk decision. Additionally, Zhang et al. (2007) found that many evacuees from Hurricane Rita focused upon the storm's meteorological characteristics and reported frequently checking multiple sources for updated forecasts throughout the process. It appears that the proportional importance of official evacuation orders and statements is decreasing as television and internet source reliance (Lee et al. 2009) is increasing over time.

As personal risk assessment becomes more commonplace and populations become more savvy in this period of heightened TC activity, researchers must take an interdisciplinary approach to mitigate possible discrepancies between warning communication, and the possible misinterpretation of that information by the public. This is especially true for future storms if a TC is expected to make landfall at a certain location and certain intensity, and fails to do so (Dillon et al. 2010). The scientific community needs to evaluate and gain a better understanding of how forecast information is being used in personal decision making (Morss et al. 2008, 2010). Hurricane warning graphics are one area where the public frequently misinterprets the intended message (Broad et al. 2007). In the 2004 hurricane season in Florida, the Cone of Uncertainty (COU) (created by the National Hurricane Center, and modified by agencies, newspapers, and broadcasters) came under criticism for possibly conveying too much certainty. Residents placed too much emphasis on the black line in the center of the cone and failed to understand that the shaded area represents the possible location of the storm at forecasted time intervals (Broad et al. 2007). Furthermore, the COU does not address the issue of storm size, which accounts for tremendous variability in spatial damage swath (Senkbeil and Sheridan 2006). Senkbeil et al. (2009) attempted to quantify evacuee error from Hurricane Gustav using survey data collected during the evacuation. Forecast accuracy from the NHC was admirable for Hurricane Gustav with only subtle changes in 6-hourly updates. Senkbeil et al. (2009) used three related methods of error assessment focusing on the differences between the perceived landfall location of evacuees and the actual landfall location. Results indicated that, regardless of location, most evacuees perceived a landfall location closer to their home zip codes than what actually occurred. A separate study from the same Gustav data (Brommer and Senkbeil 2010) asked residents to rank the meteorological hazards of Gustav at their homes. Results indicated that residents of coastal Louisiana were very knowledgeable about the hazards posing the greatest risk at their locations. This is not surprising given the region's active hurricane history (Keim et al. 2007). It appears that experienced hurricane populations are very aware of the hazards from an approaching storm, but the uncertainty in track location and storm intensity conveyed by warning graphics 72–48 h before landfall creates a post-landfall situation where the perception of expected damage may be discrepant with the perception of actual damage. In order to save time, money, and avoid confusion, the public desires a degree of forecast certainty that is currently lagging behind the precision of the demand.

5. Concluding Thoughts

In this article, we summarized the current state of hurricane impacts in the USA. There are many topics that we did not discuss, but we hope this brief review presented a balance between physical and social science research. The USA has a hurricane problem that requires interdisciplinary action. Coastal populations continue to escalate during an active hurricane phase that may continue under the potential effects of climate change. Much has been learned about hurricane hazards and the circumstances and types of TCs that produce anomalous wind, surge, tornado, and rainfall values. This information needs to find a more accessible outlet to the public and be applied in warning scenarios with greater emphasis. The authors feel that more information will only help the public and not confuse them. In fact, we believe more information may even help reduce evacuee error in forecast interpretation. More residents are listening to official warning statements, but consulting numerous sources before making their own decisions about risk and evacuation. Official forecasts issued at 72–48 h before landfall have improved rapidly and they will continue to do so; however, these forecasts currently lag behind the precision desired from the public. Until the gap can be closed between public desire for better accuracy and the technology necessary to produce that accuracy, we have a few suggestions that may initiate constructive dialog regarding the topics discussed in this article:

- Update the Saffir–Simpson Scale to include hurricane size and forward speed
  The TC scale used by the Meteorological Agency of Japan is one example of a scale that incorporated size into its warnings. The authors cannot find any information to suggest that this practice is still operational. Larger hurricanes have the potential to impact a greater population with a larger damage swath. Hurricane size also has been shown to affect storm surge potential. Slower storms have a greater potential for pro-

Table 3. Amended Saffir–Simpson scale with categories for size and forward speed. The size and forward speed categories are grouped according to natural breaks at approximately 1 SD from the sample mean. The sample includes 26 land-falling storms with available radar data since 1995.

Storm category	Wind speed range (m/s)	Size	ROCI (km)	Forward speed	Speed range (m/s)
TS	17–32	Small	<200	Slow	<4
Cat1	33–42	Medium	200–400	Medium	4–8
Cat 2	43–49	Large	>400	Fast	>8
Cat 3	50–58				
Cat 4	59–69				
Cat 5	70+				

ROCI, radius to outermost closed isobar.

lific flooding. Thus, the one to five Saffir–Simpson scale could be amended (Table 3) to have three categories for size (small, medium, large) and three categories for forward speed (slow, medium, fast). These terciles are based upon a sample of 26 land-falling storms with available radar data since 1995. This may help the public understand the differences between Hurricane Charley (2004) (category 4, small, fast) and Hurricane Katrina (2005) (category 3, large, medium). These two storms produced distinctly different hazards.

- Change the COU
  The COU currently depicts forecasted landfall time, spatial uncertainty, and current intensity. Other graphics, such as Wundermaps from Weather Underground, show a cone with forecasted intensity at landfall. We suggest a graphic similar to that of Australia's, which attempts to incorporate size using wind radii, intensity, and uncertainty of track prior to landfall all in one graphic (http://www.bom.gov.au/cyclone/about/warnings/gis.shtml). We present a hypothetical warning graphic for the USA based on the Australian graphic (Figure 3). When used in conjunction with Table 3, this hypothetical storm would be category 2, large, fast.
- Reduce evacuation travel distance and unnecessary evacuation
  Evacuations undoubtedly reduce mortality, but they can also be very chaotic and exhausting. This is especially true when inland populations not included in the mandatory evacuation decide to leave (shadow evacuation population), creating massive gridlock. Observed winds over land are consistently much weaker than winds over the open ocean (Senkbeil and Sheridan 2006; Sparks 2003), and wind results in few fatalities. Even though winds are reduced over land, locations in south Texas and south Florida receive winds closer to open ocean speeds due to lack of vegetative cover. For most category 1 and 2 Saffir–Simpson-ranked hurricanes, we suggest mandatory evacuation for only residents of low-lying coastal areas and inadequate housing (mobile homes) in elevated areas. Residents surrounded by dense tree canopy should also consider evacuating. For category 3 and 4 hurricanes, we suggest considering a shorter-distance mandatory evacuation operation where larger and more numerous shelters should be provided closer to the coast and safely away from the surge zone. Large scale mandatory evacuations on the scale of what has been observed in the past 20 years should only be exercised for rare and potentially catastrophic hurricanes; upper category 4 and category 5. A greater emphasis on hurricane hazard education we feel would inform the public about the likely conditions and hazards for different types of storms from the first bullet.

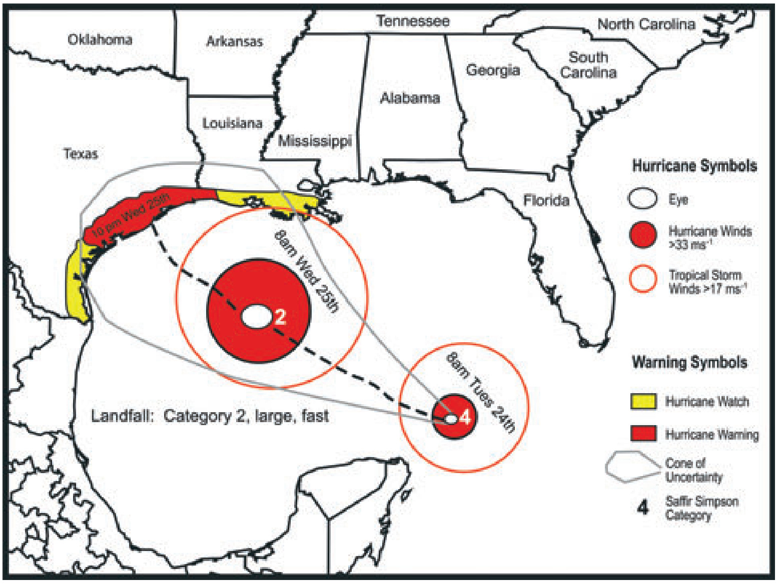

Fig. 3. Hypothetical hurricane warning graphic for the USA based on the Australian warning graphic.

• Develop improved warning discussion for the coastal to inland transition
Reducing the scale of evacuation may prove to be an unpopular suggestion. Therefore, we suggest possible enhancements to existing warnings at inland locations. Coastal residents frequently evacuate inland, temporarily swelling the populations of inland counties. This exposes inland and evacuated coastal populations to a weakened, but still significant storm. Based on the scenarios from point 1 on types of storms, more detailed inland warnings should be issued to account for storm decay. Inland flooding

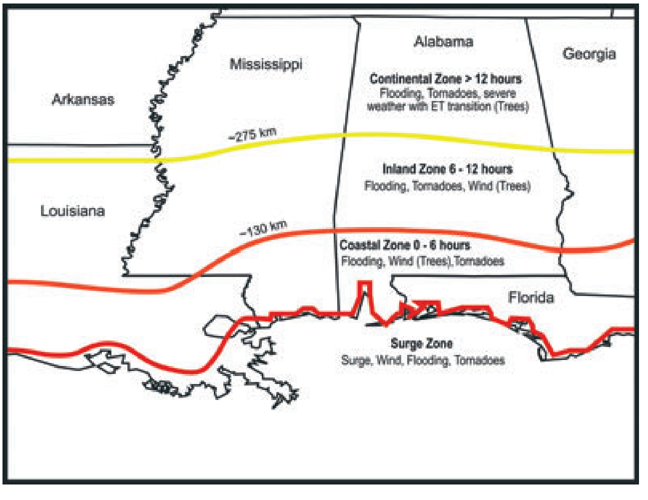

Fig. 4. Hypothetical hurricane hazard zones for a category 3, medium, medium storm making landfall on the northern Gulf Coast. Storm-specific hazards are prioritized in each zone. Post-storm morbidity/mortality may be more important than storm-specific hazards.

and tornado potential should carry more emphasis. We suggest the possibility of creating spatial hurricane hazard zones that could be adjusted for storm forward speed and unique storm attributes. We present a hypothetical hazard zoning map (Figure 4) for a category 3, medium, medium storm making landfall on the northern Gulf Coast. Hazards are prioritized in each zone. It could be argued that post storm morbidity is possibly more important than storm-specific hazards.

Short Biographies

Jason Senkbeil is a geographer–climatologist with research emphases in hurricane hazards and synoptic climatology. His hurricane hazard research is at the interface of physical and human systems focusing on the accuracy and knowledge of public perception of specific meteorological hazards. His previous hurricane research has been published in *The Journal of Coastal Research and Natural Hazards*. He has experienced numerous hurricanes of varying intensity in different locations and uses these events as valuable field experiences. He earned a BS in Geography from the University of South Alabama, an MS in Geosciences from Mississippi State University, and a PhD in Geography from Kent State University.

David Brommer is a geographer–climatologist with research interests in human–climate interactions and secular climate variability. His research in human–climate interactions has been published in the Bulletin of the American Meteorological Society, Natural Hazards, and Southeastern Geographer. More recently, he has begun analysis of microclimate environments inside large, open-air stadiums and its relation to heat stress. His secular climate variability work has been published in Climate Research, Monthly Weather Review, and Geophysical Research Letters. He earned a BS in Geoscience from Mississippi State University, a MA and PhD from Arizona State University in Geography.

Ian Comstock is a graduate student in the Department of Geography at the University of Alabama. He has dual research interests in Climatology and GIS. In his research, he uses GIS to evaluate numerous hurricane hazard variables. He earned a BS in Geography from Indiana State University and an MS in Geography from the University of Alabama.

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